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FY08 LDRD Final Report: Fundamental physical mechanisms of mitigation approaches to laser-induced damage on ultraviolet optics

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Disclaimer

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FY08 LDRD Final Report
Fundamental Physical Mechanisms of Mitigation Approaches to Laser-Induced Damage on Ultraviolet Optics

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Vaughn Draggoo, Principal Investigator

Abstract

The objective was to explore and further develop the concept that laser–induced damage on surfaces of an optic can be mitigated to extend its lifetime in high-fluence laser systems. The project scope explored mitigation processes utilizing laser, micro-machining, and chemical techniques including laser-induced damage testing of the mitigated site, and characterization of the size and shapes of the mitigation site with respect to downstream intensification of the high energy laser beam. Advanced materials processing and characterization tools, and computational tools were developed to investigate physical properties of the mitigated regions. The material focus of the mitigation effort was fused silica and potassium di-hydrogen phosphate (KDP) crystal optics. and to develop a A fundamental understanding of the physical mechanisms of the mitigation processes is sought in order to extend their applicability to larger and deeper damage sites and to larger laser fluences. When successful, these mitigation processes will significantly extend the useful lifetime of the optic and drastically reduce the associated operating costs.

For silica optics, mitigation processes utilizing mid-infrared (4.6 μm) and far infrared (10.6 μm) laser radiation from carbon dioxide lasers was used to ablate, evaporate, melt and anneal the damaged silica surface. By varying the laser parameters (power, pulse rate, spot size, etc.) these investigations evaluated the almost 100x difference in the optical absorption depth between these wavelengths in the efficacy in arresting damage growth, and controlling the end-state of the material in terms of shape morphology, residual stress and process by-products (vapor and re-condensed material).

For crystal optics, micro-diamond tool machining and micro re-crystallization of KDP were investigated. A precision three-axis micro machine tool was developed, tested and shown capable of treating damage sites to 1 mm in size that were robust against re-initiation of damage and exhibited acceptable downstream intensification. Micro re-crystallization of KDP was accomplished through Gibbs-Thompson condensation at the tip of an Atomic Force Microscope stylus. By controlling the humidity at the tip and raster scanning of the stylus over damaged crystal surfaces, filling of scratched surfaces with re-crystallized material was demonstrated.

Introduction and Background

The objective of this project was to develop a comprehensive, science-based understanding of the fundamental physical principles guiding the development of strategies to mitigate laser-induced damage growth on inertial confinement fusion (ICF)-class laser optical components. Specifically, fundamental computational and experimental investigations were conducted for damage-mitigation strategies on fused silica (FS, amorphous SiO_2) and potassium dihydrogen phosphate [KDP, chemical formula KH_2PO_4] crystals. These investigations integrated exploratory mitigation processes, high-performance modeling and simulation, and advanced diagnostics development and materials characterization to investigate the fundamental materials properties of the mitigated region.

Laser-driven inertial confinement fusion (ICF) requires the use of Mega-Joule (MJ)-class high-fluence ultraviolet (UV) lasers. Under such operating conditions, individual optical components within the laser system can incur physical damage (typically the formation of small craters on the surface), leading to unacceptable performance degradation. In the early stages of repeated laser irradiation, the damage sites of an optical component are small and do not significantly interfere with the performance of the laser, Fig. 1. However, if the sites experience additional exposure to the high-fluence laser, they can grow exponentially in size with shot count. Eventually, the scattering losses will exceed the limit beyond which the laser is no longer usable without replacing the damaged optical component — resulting in high operational costs. Consequently, effective and robust damage mitigation strategies must be established and implemented to overcome this problem.

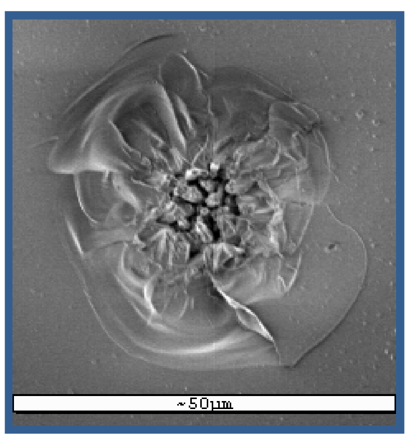


Figure 1: SEM image of exit surface damage site in silica.

The proposed mitigation development activity addressed both fused silica and KDP. The consideration of both fused silica and KDP is important because significant differences exist in the fundamental physical properties of these two materials — in regard to mechanical strength, chemical reactivity, optical anisotropy, and melting/transition points. Throughout the effort, the emphasis was on the development of a science-based and predictive understanding of the fundamental materials science aspects and physical phenomena underlying the mitigation processes under investigation.

Conceptually, the mitigation process removes or modifies material from a damage site in such a way as to smooth the surface, heal or eliminate subsurface cracks, and reduce residual stress in the remaining “divot” (Fig. 2a and 2b). Operationally, the criteria for successful damage mitigation include:

- No further observable local damage (i.e. growth) at the site upon subsequent pulsed UV laser irradiation;
- Acceptable downstream intensification of UV light from the damaged and/or mitigated site;
- Acceptable impact on the ability to coat the optical component after mitigation; and
- High confidence that sites needing mitigation have been successfully repaired.

Within the scope of the proposed effort, we explored the fundamental physical mechanisms governing mitigation processes that exploit laser, mechanical, and chemical-based techniques — individually or in combination, when appropriate — for damaged material removal, crack healing and surface smoothing. In order to be successful and provide as much flexibility as possible for high-fluence laser operations, it is desirable to develop a robust process that can mitigate a broad range of damage sites with various sizes and shapes. This research effort addressed all these success criteria.

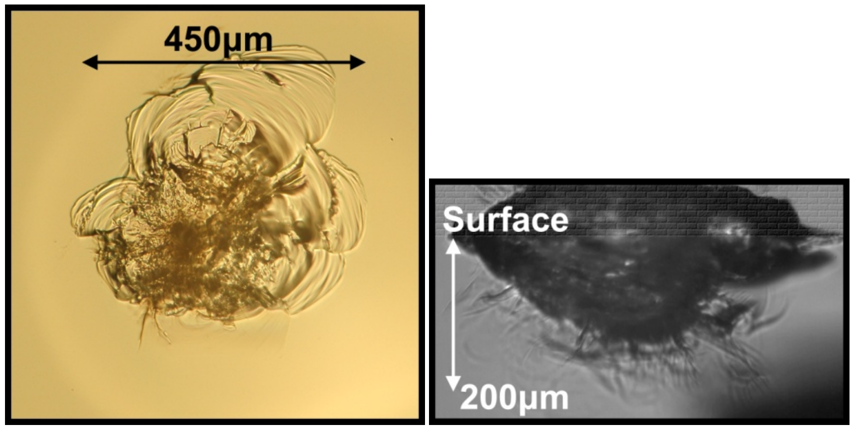


Figure 2a: Micrographs of a damage site on the exit surface of fused silica extending 450 μm laterally (left) and 200 μm axially (right). Note the extent into the depth of the subsurface cracks.

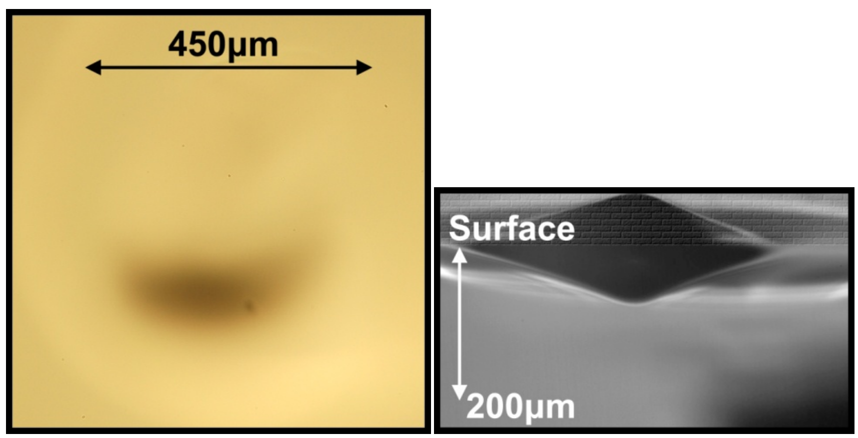


Figure 2b: Micrographs of the damage site in 2a following mitigation using a mid-IR (4.6μm) laser. This figure illustrates the “healing” of subsurface cracks and smoothing of the damage site.

Laser-based mitigation techniques for fused silica

Conceptually, the general approach to mitigation of UV laser-induced surface damage is illustrated in Fig. 3. Infrared laser light from a CO_2 laser is strongly absorbed by fused silica, and by carefully controlling the laser beam power density the physical state of the damage site can be altered to render the remaining site robust against subsequent high fluence laser light, and not refract and/or diffract the light in ways that can lead to downstream intensification resulting in damage to other optics.

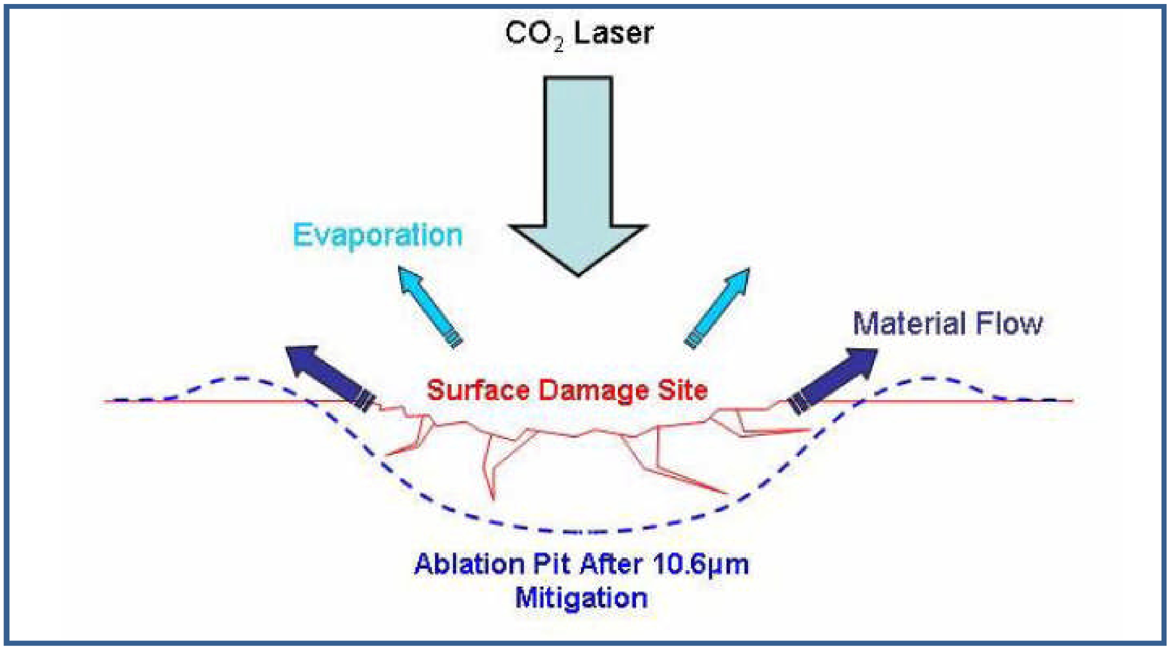


Figure 3: schematic of the mitigation process using CO2 laser techniques

As silica exhibits strong sensitivity of the thermo-physical properties with temperature, time-dependent thermal, optical and mass transport phenomena are difficult to manage in a satisfactory and predictable way. For example, while the end-state of the mitigation pit (dotted line in Fig. 3) may be robust to subsequent laser exposure, evaporated material can re-condense and lead to laser damage on the margins, and/or material flow due to capillary forces can lead to unacceptable surface profile leading to downstream intensification.

Our research efforts explored using a CO_2 laser operating at 10.6 μm and a frequency-doubled CO_2 laser operating at 4.6 μm to perform the mitigation process. The general empirical approach included investigation of beam delivery and control techniques, material property diagnostics (like surface and bulk morphology, and residual stress), laser propagation modeling and testing, and damage testing.

The following publications describe this laser-based mitigation research:

Guss, G. M., et al., 2007, *High-resolution 3-D imaging of surface damage sites in fused silica with optical coherence tomography,* Laser Induced Damage I Optical Materials. 39th Annual Boulder Damage Symp., Boulder, CO, Sept 24-26, 2007. UCRL-PRES-234640.

Matthews, M. J., et al., 2007, *Downstream intensification effects associated with CO2 laser mitigation of fused silica*, Laser Induced Damage in Optical Materials, 39th Annual Boulder Damage Symp., Boulder, CO, Sept 24-26, 2007 UCRL-POST-234882.

Matthews, M.J. and M.D. Feit, 2007, *Effect on random clustering on surface damage density estimates*, Laser Induced Damage in Optical Materials, 39th Annual Boulder Damage Symp., Boulder, CO, Sept 24-26, 2007 UCRL—PRES-234637.

Guss, G. M., et al. 2006, *Mitigation of growth of laser initiated surface damage in fused silica using a 4.6um wavelength laser*, Laser Induced Damage in Optical Materials, 38th Annual Boulder Damage Symp., Boulder, CO, Sept 25-27, UCRL ABS-221869

Bass, I. L., et al., 2005, *Mitigation of laser damage growth in fused silica with a galvanometer scanned CO2 beam*, Laser Induced Damage in Optical Materials, 37th Annual Boulder Damage Symp. Boulder, CO, Sept 19-21 2005

Bass, I. L., et al., 2006, *Mitigation of laser damage growth in fused silica NIF optics with a galvanometer scanned CO2 laser*, 2006 SPIE "High Power Laser Ablation", Taos, NM., May 7-12, 2006 UCRL-PROC-220549.

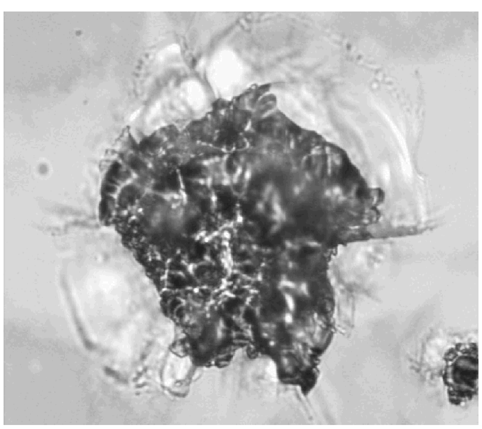
Mitigation techniques for Crystalline KDP

Micro - Machining

Macroscopic diamond tool machining of potassium dihydrogen phosphate crystal to produce high quality optical surfaces for large aperture, 10’s of kilojoule per aperture laser systems is a highly developed technology; it is the fundamental production method for the frequency conversion and polarizing optical elements of the NIF laser system. For damage site mitigation in KDP, micro-machine tools designed to operate in the same ductile machining regime, but at much smaller spatial scale, were applied to the KDP damage problem. Similar to the case of fused silica, a successful mitigation process must:

- Remove UV laser-induced damage debris in a manner that does not contaminate the remaining and adjacent areas around the site. This debris can cause initiation of secondary damage;
- Form a robust, but not necessarily a high optical quality, machined surface;
- The site morphology must not cause excessive downstream intensification due to refractive and diffractive effects caused by the machining process.

A process to stabilize laser-initiated surface damage on KDP/DKDP by micro-machine contouring using a single-crystal ball nose end mill has been shown to mitigate damage growth for subsequent laser shots. Careful testing has shown that machined circular contours on output surfaces of uncoated doubler (KDP) and tripler (DKDP) crystals are stable for laser exposures at 351 nm, ~8-10 ns pulses at 12 J/cm^2 fluence.



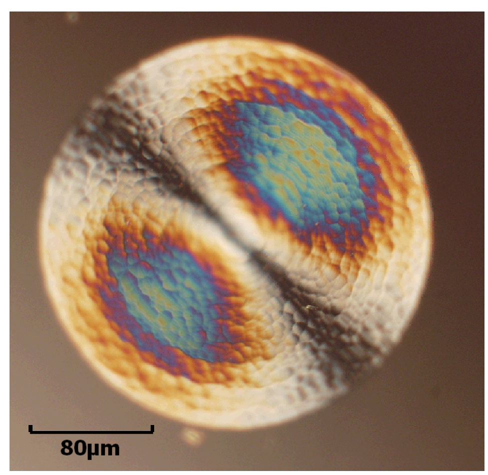


Figure 4: Micrographs of exit surface damage pit on KDP (left) and a completed machined surface (right) capable of withstanding subsequent laser shots.

Within the constraints of the geometry of the micro-machine tooling, the mitigated site profile is deterministic and can be specified to minimize downstream intensification caused by diffraction. Analysis and testing has shown the simple "cone" profiles, like the one shown in Fig. 4, yield optimum results.

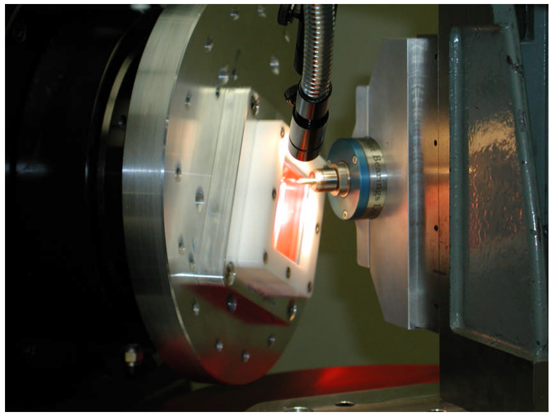


Figure 5: a 100μm (radius) single crystal diamond ball-end mill rotating at 70,000 rpm in a precision tooling system applied to a KDP optic sample.

Publication:
Geraghty, P., et al., 2006 *Surface damage growth mitigation on KDP/DKDP optics using single-crystal diamond micro-machining ball end mill contouring,* Laser Induced Damage in Optical Materials, 38th Annual Boulder Damage Symp., Boulder, CO, Sept 25-27 UCRL-POST-??????

Solvent-mediated repair

A tip-based approached to shaping surfaces of KDP (a water soluble material) with nanometer-scale control was explored as an approach to repair laser damaged KDP. The phenomenon that enables the repair of surfaces is based on the transport of material from regions of high to low curvature within the solution meniscus formed in a solvent-containing atmosphere between the surface and an atomic force microscope (AFM) tip. Using *in situ* AFM measurements of the kinetics of the surface remodeling on KDP crystals in humid air, is was shown that redistribution of solute material during relaxation of grooves and mounds is driven by a reduction in surface free energy as described by the Gibbs-Thompson law.

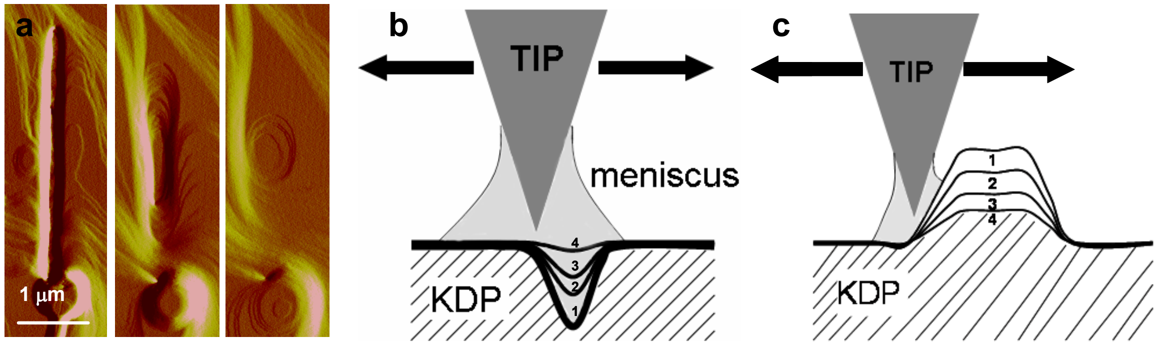


Figure 6: (a) Sequence of AFM deflection images of KDP (100) surface showing the in-filling of the groove made by tip scratching. The KDP material excavated during the scratching was re-deposited at the lower end of the groove on the image and dissolves over time. This surface remodeling occurs in a humid air environment which produces an aqueous meniscus as depicted in the (b) schematic of the time evolution of the in-filling of the groove (1-4), and in the (c) schematic of the evolution of the dissolution of the mound shown (1-4).

It was found that the perturbation from a flat interface evolves according to the diffusion equation, where the effective diffusivity is determined by the product of the surface stiffness and the step kinetic coefficient. It was also shown, surprisingly, that if the tip is instead scanned over or kept stationary above an atomically flat area of the surface, a convex structure is formed, with a diameter that is controlled by the dimensions of the meniscus, indicating that the presence of the tip and meniscus reduces the substrate chemical potential beneath that of the free surface. This allows creation of nanometer-scale 3D structures of arbitrary shape without the removal of substrate material or the use of extrinsic masks or chemical compounds.

Publications:

S Elhadj et al, (2008) “Solvent-mediated repair and patterning of surfaces by AFM”, *Nanotechnology*, 19(10), 105304. UCRL-JRNL-236360

S.W. Chung et al, (2008) “Scanning probe-based fabrication of 3D nanostructures via affinity templates, functional RNA, and meniscus-mediated surface remodeling”, *Scanning*, 30(2) 159. UCRL-JRNL-235551

Conclusions

Damage mitigation techniques suitable for fused silica and crystalline KDP were demonstrated. For fused silica, both far- and mid-IR laser-based techniques yielded good results in terms of downstream modulation and damage re-initiation, with the latter producing very little re-deposit. KDP, on the other hand, was shown to be more amenable to mechanical mitigation techniques based on ductile micro-diamond-machining, which removed damaged material leaving behind a damage resistant cone-shaped divot. Exploratory work on solvent-mediated mitigation and micro-patterning of KDP surfaces using an AFM tip also showed promise as a possible alternative to micro-machining.

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